
First International Symposium on Mine Safety Science and Engineering

Causes of Spontaneous Combustion of Coal and Its Prevention Technology in The Tunnel Fall of Ground of Extra-thick Coal Seam

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Abstract

On the basis of the four factors of spontaneous combustion of coal, the causes of such combustion in the tunnel fall of ground were comprehensively analyzed. The causes include the generation of float coal, influence of hot wind pressure on the laneway, and airflow dynamic pressure caused by sloping roadways. According to the characteristics of a fire that occurred in the intake airflow roadway of working face 12190 in the Geng Cun Coal Mine, a three-phase foam composed of mud, nitrogen, and water was used to extinguish the fire. The foam was injected into the fire zone through boreholes on the tunnel roof. Given the precise scheme and reliability of the technology, the fire was successfully extinguished. The specific technological process and parameters of the technology are discussed in detail. It is concluded that the three-phase foam is useful in preventing spontaneous combustion of coal in the tunnel fall of ground. It serves as a new method for preventing such phenomenon in extra-thick coal seam.

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Selection and/or peer-review under responsibility of China Academy of Safety Science and Technology, China University of Mining and Technology(Beijing), McGill University and University of Wollongong.

Keywords: Spontaneous combustion of coal, tunnel fall of ground, three-phase Foam, application

1. Introduction

The spontaneous combustion of coal is one of the major hazards encountered in the coal mines of China. Statistics show that in 1993, 361 coal mines (accounting for 55% of the producing coal mines in the country)

The spontaneous combustion of coal in high caving regions is a kind of internal fire in a specific environment of underground coal mines. Its prerequisite is the appearance of caving in the tunnel, while the fire is sheltered by supports. Consequently, the spontaneous combustion of coal in the caving region is more concealed and dangerous than any other fires. Fires stemming from the spontaneous combustion of coal are difficult to put out.

To prevent mine fires, various traditional technologies have been developed and applied all over the world^[7-15]. Such technologies include water and grouting injection, gelatum infusion, inert gas injection, and so on. These technologies played an important role in ensuring mining safety. However, traditional technologies suffer from limitations in preventing fires in high caving. For example, gelatum, which consists of sodium silicate and ammonium salt, emits ammonia, a toxic gas. High molecular gelatum and foamed resin are expensive. Inert gases are prone to diffusion with airflow and cannot remain in the area where they are needed. Water and grouting injection easily flow away along the cracks of the tunnel roof. All of these methods cannot efficiently prevent spontaneous combustion in the tunnel fall of ground. In this paper, we present an application of a new technology named three-phase foam^[16]. This technology was successfully employed in the Geng Cun Coal Mine in Henan Province to extinguish an extraordinarily serious mine fire that occurred in the high caving region of the tunnel.

2. Causes of coal spontaneous combustion in the tunnel fall of ground

Whether coal seam with spontaneous combustion tendency can gradually burn depends mainly on the following factors^[17]: (1) the existence of numerous crumbling float coal; (2) sufficient oxygen supply; (3) contribution to heat storage from the surrounding environment; and (4) an oxidation reaction time that is longer than the spontaneous combustion period of coal. The absence of any one of the four factors prevents the spontaneous combustion of coal. On the basis of these factors, we analyze the causes of the spontaneous combustion of coal in the tunnel fall of ground in the intake airflow roadway at the 12190 working face of the Geng Cun Coal Mine.

2.1. Massive float coal in the region exposed to air for long periods

The tunnel fall of ground is the most important factor in the spontaneous combustion of coal in the tunnel fall of ground. The formation of this region depends primarily on the geological structure and quality of tunnel construction. The tunnels of fully mechanical top-coal caving working faces are generally excavated along the seam floor, leaving thick coal at the top of the tunnels. After tunnel construction, the original balance of formation pressure is typically destroyed in a certain segment of the roadway because of stress concentration. Therefore, the tunnel fall of ground, where tunnel caves are prone to occur, is characterized by particularly strong ground pressure, which results in local pressure concentration^[18]. Three regions can be divided on the basis of the fissure distribution in loose coal at the top-coal caving region, degree of coal looseness, and caving level. These regions are the cracked, separation, and fault subsidence areas (Figure 1). The coal is completely cracked and the stress is fully released in the cracked area, producing about 2 to 3 m of float coal with a natural accumulation state. The air in the tunnel can easily penetrate into the loose coal through fissures in this region, a phenomenon that facilitates oxidation reaction in the coal fissure surface. Therefore, the spontaneous combustion of coal tends to occur in this region.

Cracked coal is exposed to air when tunnel caving forms. Because the period of remaining tunnel construction and coal mining cycle of the working face is very long (far longer than that of spontaneous coal combustion), there is sufficient time to maintain the development of coal oxidation and spontaneous combustion.

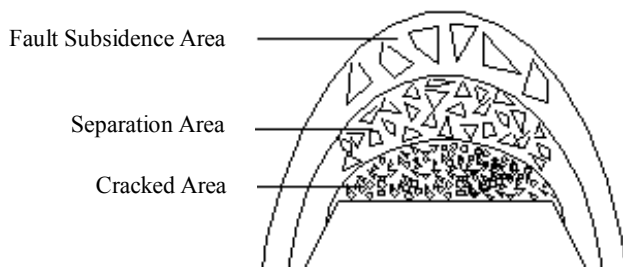


Fig. 1 Distribution sketch map of region caving in the top-coal caving region

2.2. Sufficient air leakage provides continuous oxygen supply for spontaneous coal combustion

Continuous oxygen supply is one of the determining factors for the spontaneous combustion of coal. Based on the particularity of the oxygen supply method for the float coal in the tunnel fall of ground region, through analyzing the top-coal caving region in intake airflow roadway of 12190 working face, two ways were found by which air leakage is produced^[19]: (1) hot wind pressure caused by the temperature difference between internal coal and tunnel; and (2) dynamic differential pressure generated by an undulating tunnel.

2.2.1 Hot wind pressure

After the oxidation of float coal in the tunnel cave fall of ground, temperature rises and a temperature difference occurs between the tunnel cave fall of ground and the tunnel below, resulting in hot wind pressure^[20]. The low-temperature airflow in the tunnel naturally flows to the top of tunnel cave fall of ground under the effect of hot wind pressure, thereby creating continuous oxygen supply for spontaneous coal combustion. The formula for calculating the hot wind pressure is

$$H_r = \int_0^L (\rho_\infty - \rho_x) g dx \quad (1)$$

where H_r is the hot wind pressure; ρ_∞ is the density of airflow in the tunnel; ρ_x denotes the air density of the area where the distance between coal and the roof of tunnel is x , g/cm^3 ; L represents the vertical distance between the area where roof temperature is equal to the original temperature and the top of the tunnel cave fall of ground (also called depth of caving, m); and g is the acceleration of gravity, m/s^2 .

According to J.Boussinesq's assumptions, we know that

$$\rho_\infty - \rho_x = \rho_\infty \beta (T_x - T_\infty) \quad (2)$$

where T_x is the air temperature of the area where the vertical distance between coal and the top of the tunnel cave fall of ground is x , °C; T_∞ is the temperature of tunnel airflow, °C; β denotes the volume expansion coefficient of fluid, defined as

$$\beta = \frac{1}{v} \left(\frac{\partial v}{\partial T} \right)_p \quad (3)$$

where v is the specific volume of air, cm^3/g ; T is the temperature of ideal gas, °C; P represents the pressure of ideal gas, Pa .

As to the ideal gas,

$$Pv = RT, \left(\frac{\partial v}{\partial T} \right)_p = \frac{R}{P} \quad (4)$$

where R is the molar constant.

Then, the volume expansion coefficient of air can be obtained by

$$\beta = \frac{1}{v} \frac{R}{P} = \frac{1}{T} \quad (5)$$

Therefore, hot wind pressure can be expressed as Eq. (6) thus:

$$H_r = \int_0^L \rho_\infty g \frac{T_x - T_\infty}{T_x} dx \quad (6)$$

From the theoretical analysis above, we conclude that the hot wind pressure is related to the depth of caving and the temperature difference between the upper and lower part of the tunnel cave fall of ground. The deeper the depth of caving, the greater the temperature difference and hot wind pressure, which can result in a greater amount of air leakage. When the depth of caving is constant, hot wind pressure is related only to the temperature difference between the upper and lower part of the tunnel cave fall of ground. The greater the temperature difference, the greater the temperature gradient of the float coal in the caving region and the roof of tunnel causing higher hot wind pressure and larger intensity of air leakage. At the same time, the longer the high caving existing, the more heat gathering, and this brings forth a more prominent hot wind pressure.

causing the airflow penetrate into the coal. Airflow dynamic pressure can be expressed as

$$H_v = \frac{1}{2} \rho_g \bar{v}_g^2 \sin \theta \quad (7)$$

where H_v is the difference of dynamic pressure generated by an undulating tunnel; ρ_g is the airflow density in the tunnel, g/cm^3 ; And \bar{v}_g represents the average velocity of airflow, m/s .

Eq. (7) shows that the difference of dynamic pressure H_v is directly proportional to average velocity of airflow \bar{v}_g , as well as the sine of the angle between the airflow direction and tunnel axis. The greater the average velocity of airflow \bar{v}_g and θ , the higher the airflow dynamic pressure H_v generated by an undulating tunnel, causing intensified air leakage. These phenomena are attributed to the very high wind velocity in this section of tunnel and a transition angle of 11° - 13° from the seam floor to the top of the coal roof. Therefore, high dynamic pressure occurs, providing continuous power for air leakage.

2.3. Distribution of the void in float coal at the caving region creates good heat storage conditions for coal oxidation

As for the float coal, the relationship between oxidized heat production and dissipation depends on the distribution of porosity in the coal^[21]. The capacity of loose coal heat is expressed as

$$\rho_c C_c = n \rho_g C_g + (1-n) \rho_m C_m \approx (1-n) \rho_m C_m \quad (8)$$

The thermal conductivity of the loose coal is

$$\lambda_c = n \lambda_g + (1-n) \lambda_m \quad (9)$$

where C_c , C_g , and C_m are the heat capacity of float coal, air leakage flow, and coal, respectively, $\text{J/(g} \cdot ^\circ\text{C)}$; ρ_c , ρ_g , and ρ_m are the density of float coal, air leakage flow, and coal, respectively, g/cm^3 ; λ_c , λ_g , and λ_m represent the thermal conductivity of float coal, air leakage flow, and coal, respectively, $\text{J/(g} \cdot \text{s} \cdot ^\circ\text{C)}$.

The heat capacity of air is far smaller than that of coal, indicating that the greater the porosity, the smaller the heat capacity of the entire float coal. Therefore, under the same conditions of oxidation-produced heat, the temperature of float coal rises higher, contributing to the further oxidation. Thus, the greater porosity is conducive to the spontaneous combustion of loose coal because of temperature rise resulting from heat storage.

The comparison of the thermal conductivity of air with that of coal shows that the thermal conductivity of air, which can be regarded as approximately adiabatic, is small. Therefore, the greater the porosity, the smaller the thermal conductivity of the entire float coal. This phenomenon is beneficial to heat storage. Therefore, under the same conditions of oxidation-produced heat, the temperature of float coal increases, so that the porosity imposes a more considerable effect on the temperature rising of spontaneous combustion coal. The greater the n , the smaller the thermal conductivity and heat capacity of float coal, easily increasing coal temperature and spontaneous combustion.

3. Prevention technology for fire in the tunnel fall of ground region

3.1. Three-phase foam for mine fire prevention

The three-phase foam, which can be applied in the prevention of spontaneous coal combustion, is composed of non-combustible material (ash fly, yellow mud, etc.), inert gas (nitrogen), and water, which are all effective materials for fire control. First, the foaming agent is added to the ash fly or yellow mud, and then nitrogen gas is injected. Through physical mechanical stirring by the foaming generator, the multi-phase medium is formed with particles of fly ash or yellow mud attached to the bubble surface equably. This multi-phase medium is called the three-phase foam.

Compared with pre-existing technology and materials for fire control, the three-phase foam presents the advantages of both grouting and inert gas foam in controlling fire^[22]. A large amount of three-phase foam forms after nitrogen is infused into the slurry containing foaming agent; the volume of the foam sharply increases. It can stack upon itself, which helps fill the fire area and cover the coal left in the goaf (Fig. 2). The nitrogen encapsulated in the foam can remain a longer time fire area to extinguish the mine fire. In addition,

also involves a simple technological process.



Fig. 2. Three-phase foam produced in roadway.

3.2. Application craft and parameters of the three-phase foam

The technological process of three-phase foam is shown in Fig.3. First, the mud is washed using a high pressure water gun to form the initial slurry, and then the slurry flows through two filters. Finally, the compound slurry with a mud-to-water ratio of 4:1 is prepared in the slurry mixing tank. The prepared slurry was then pumped into the grouting pipes where the foaming agent was introduced by volumetric screw pump in the proper proportion. The slurry and foaming agent was fully mixed and then delivered into the foaming generator. Nitrogen gas was added into the foaming generator through a rubber pipe, and three phase foam was formed following the interaction between the gas and slurry. Finally, the three-phase foam is delivered to the fire zone through boreholes.

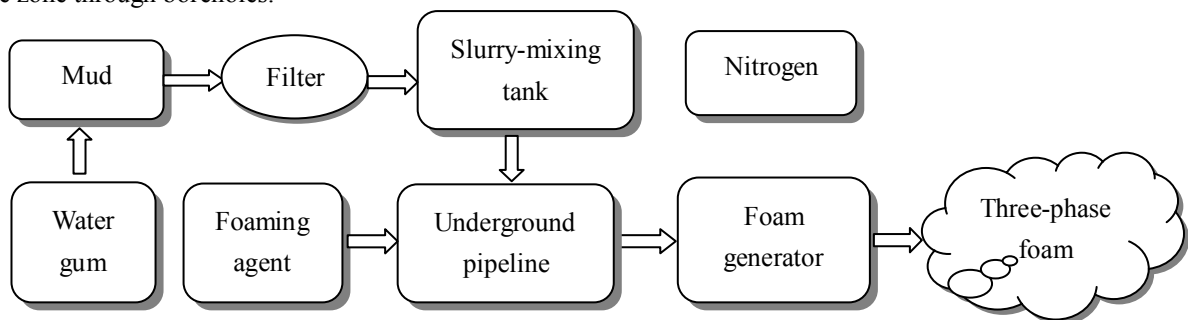


Fig.3 Craft process of infusing the three-phase foam

Considering the technological process of the three-phase foam and the actual conditions of the mine, the main technical parameters were showed. (Table 1).

Table 1 Main technical parameters of infusing the three-phase foam

Quantity of slurry (m ³ /h)	Ratio of mud to water	Quantity of air (m ³ /h)	Foaming multiple	Rate of foaming agent consumption (t/h)	Transmission times of line
20	1:4	600	≥30	0.1	5.3

4. Application Example

4.1. Occurrence of the fire

Gengcun Coal Mine, which is part of the Yima Mining Industry Group, is located in the west of Henan Province. The mine is started production in 1982. At that time, the mine produced 1.2 Mt/a. This was raised to

strike direction of the working face is 1060 m long, and the slope direction is 170 m long. The thickness of coal seam is 11–15 m, and the dip angle is 9–13°. The shed of this working face roadway is supported by type #11 joist steel, and the distance of the two sheds is 0.5 m. Beam length is 3.1 m. Column length is 2.8 m. A metal mesh (1000 mm × 600 mm) covered with color cloth is located on the beams. Because the tunnels are driven along the seam floor, roughly 8 m of coal is maintained at the top of the tunnel.

The intake and take roadway of the 12190 working face was breakthrough on 24 October 2005. The amount of wind was 1100 m^3/min and mash gas concentration in return air was 0.6%–0.7%. Smoke was found in the air-intake roadway at a distance of 892 m toward the working face by a ventilated worker on October 30. Traditional techniques, such as drilling and grouting, were adopted to extinguish the fire. However, because the tunnel was near the fault, coal became very soft, and the tunnel transits from the seam floor to the top of the coal roof at an angle of 11°–13°, aggravating the conditions of the coal at the top of the tunnel break. This forms a larger cave on the roof. Therefore, the area of the tunnel fall of ground was large and air leakage became serious. At the same time, the wind speed at the working face was too fast (higher than 2 m/s), and mash gas was accumulated in the tunnel fall of ground region. The area of the fire expands continuously, therefore, the local explosions were happened intermittently, and the CO concentration increased sharply. The CO concentration was 800 ppm in the intake roadway on the morning of November 3, but increased sharply to 1800 ppm on November 4, accompanied with smoke billowing in the tunnel. The visible distance was less than 0.5 m. Traditional techniques had little effect on the fire, and the whole mine safety was confronted with serious hazards.

4.2. Implementation and effect of the three-phase foam

Under the instruction of researchers from China University of Mining and Technology, a plan was developed for infusing three-phase foam to fight the fire at the Gengcun Coal Mine. The implementation is described as follows. The workers drilled boreholes near the fire area in intake roadway to accurately determine the fire area which length was 110 m (Fig.4). A row of drilling was set every 3 m, with two holes in each row; the depth of each hole depended on whether it had reached the roof of the caving. After the drilling was completed, a $\Phi 38$ mm steel pipe was placed into the borehole (Fig.5). More than 10 holes were marked at the front of each pipe at intervals, and the diameter of each hole was 20 mm. After all the drillings were arranged, massive quantities of the three-phase foam were grouted into the underground fire zone through drill. The foam accumulated rapidly, which rapidly covered the fire area. This effectively stopped the spread of the mine fire. The nitrogen released from the three-phase foam kept the fire area smothered. As a benchmark gas, the concentration of CO decreased successively (Fig.6). we can see that the fire was quickly extinguished. Fig.7 shows the original tunnel fall of ground fire area and boreholes after extinguishing.

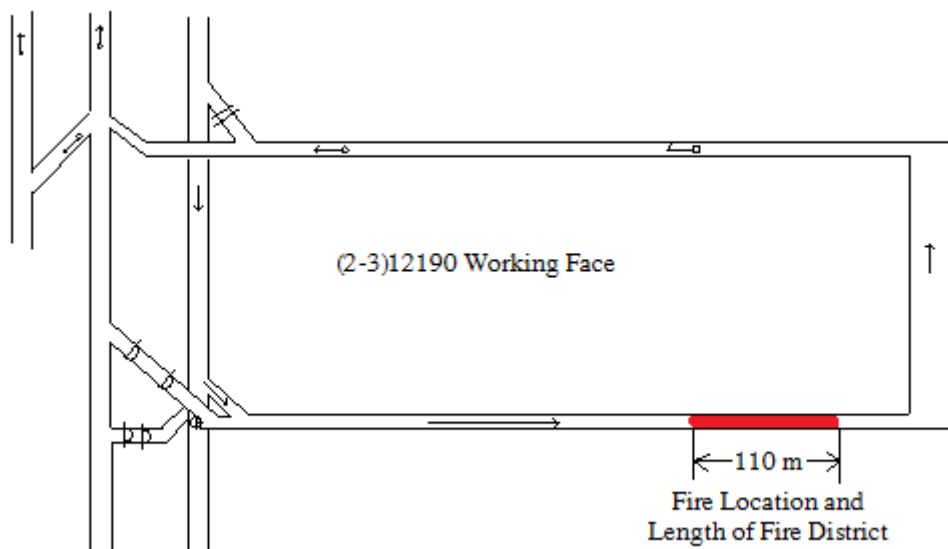


Fig.4 Position of the fire area in the entire working face

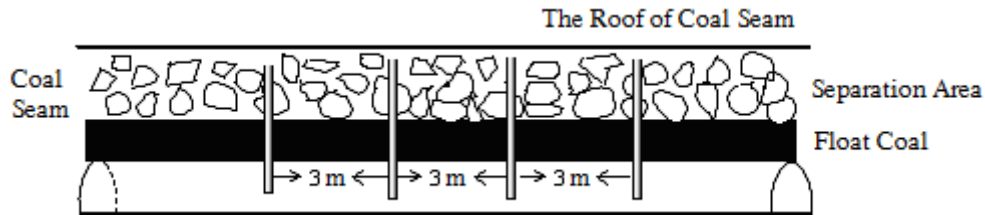


Fig.5 Diagram of drilling arrangement in the tunnel fall of ground region

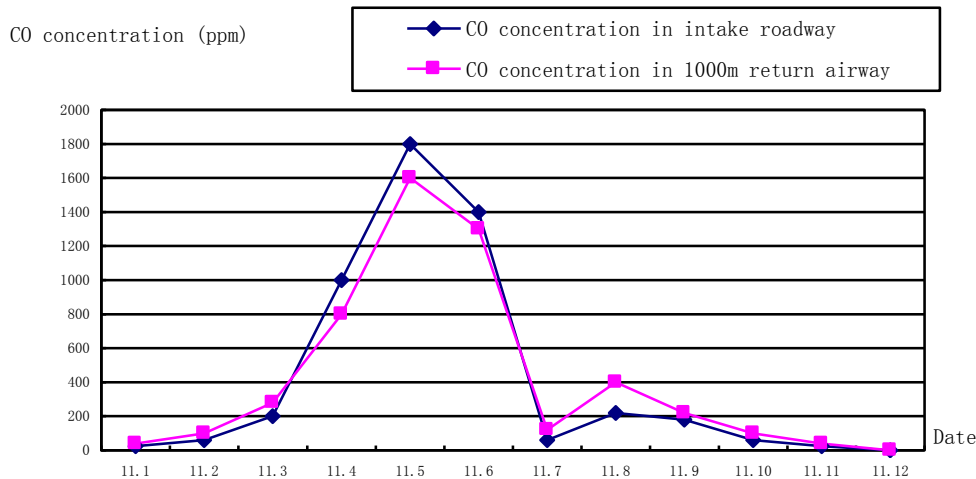


Fig.6 Variation curves of CO concentration and time at the 12190 working face

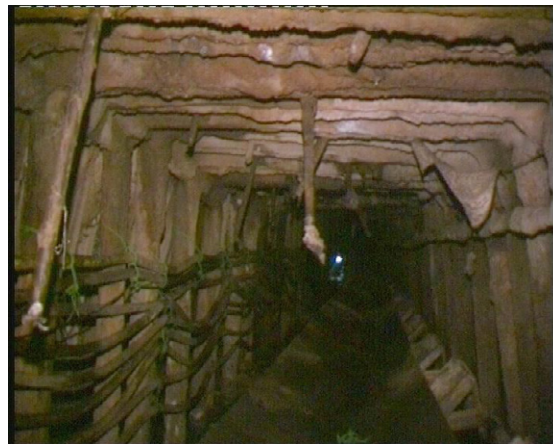


Fig.7 Original tunnel fall of ground fire area and boreholes after the fire was extinguished

5. Conclusions

This paper analyzed the causes of coal spontaneous combustion in the tunnel fall of ground region, and presented the application of grouting three-phase foam massively through boreholes drilled to extinguish an extraordinarily serious mine fire of extra-thick coal seam in the tunnel fall of ground. From this work, the following conclusions reached:

(1) As a new anti-fire material, the three-phase foam not only prevents the coal spontaneous combustion of the fully mechanized working face in the goaf and extinguishes extensive fires, but also enables the prevention of the tunnel fall of ground fire area. The three-phase foam can rapidly accumulate upward in the fire area, thereby effectively preventing the spontaneous combustion of float coal located in low and high areas. The non-combustible material of the three-phase foam can cover the float coal. The water in the three-phase

large capacity, simplicity, reliability, and so on. Specifically, the three-phase foam can cover the fire area quickly over a large area, so the fire can be extinguished quickly and effectively. The three-phase foam has outstanding extinguishing features with higher efficiency compared with any other technique.

(3) The three-phase foam was applied to the tunnel fall of ground region of the 12190 intake roadway to prevent float coal spontaneous combustion in the Gengcun Coal Mine. The foam is proven effective, guaranteeing the safety of the working face.

Acknowledgements

The authors would like to thank the engineering technicians of Yima Mining Industry Group for their devoted help. The financial support by the Natural Science Foundation for innovative scholar of Jiangsu province (No. BK2009004) and the Fundamental Research Funds for the Central Universities (No. 2011QNB11).

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